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STUDIES OF REFLECTION CHARACTERISTICS OF THE PLANET EARTH FROM A SYNCHRONOUS SATELLITE - PRELIMINARY RESULTS-

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ABSTRACT

Digitized data of nine ATS-1 photographs taken on 21 and 22 April 1967 were used to study statistically the dependence of reflection properties of the earth-atmosphere system on the zenith and azimuthal angles of measurement and on the zenith angle of incident solar radiation. Four states of the sky were defined for this study: "complete overcast," "cloudy-overcast," "cloudless atmosphere," and "minimal reflection." The limited quantity of data analyzed so far provides sufficiently accurate results only for small solar zenith angles ($0.0° \leq \zeta \leq 25.8°$). A remarkably high reflection was found in all conditions in a small angular range around the specular point of the sun on the earth's surface. The horizon appeared to be brighter than other areas for "cloudless atmosphere" conditions only. A maximum of reflected solar radiation due to direct backscattering was not found in these preliminary results.

CONTENTS

INTRODUCTION

Scattering processes in the atmosphere and reflection from ground and cloud surfaces cause part of the incident solar electromagnetic radiation to be lost to space without exchanging its energy with these scatterers and reflectors. The accurate calculation of this radiation flux is of importance in studies of the heat budget of the earth-atmosphere system. These scattering and reflection processes have been studied experimentally and theoretically by many researchers in the past, all of whose results showed that these processes cause an anisotropic field of solar radiation reflected back to space. This anisotropy must be taken into account in determining the reflected flux from "beam" measurements of reflected solar radiation made by satellite-borne instruments.

A first attempt in this direction (RASCHKE and PASTERNAK, 1967) led to reasonable results of the earth's extraterrestrial radiation balance and the earth's albedo. However, the assumptions underlying that study need to be further defined due to the limited amount of data which was available at the time to formulate them.

Several authors (see e.g. RUFF et al., 1967) have previously studied statistically the dependence of satellite beam measurements of reflected solar radiation on the angles of measurement and on the zenith angle of incident solar radiation. Their results generally confirmed the angular reflection characteristics which have previously been predicted theoretically. But a basic limitation existed in the data available to these workers, caused by the rather wide aperture angle (~ 70 mrad) of the scanning radiometers flown on the TIROS and Nimbus satellites, which did not permit accurate studies of reflected radiation close to the earth's horizon.

The camera of the satellite ATS-1 has a field of view of only 0.1 mrad at the 50% response level (Ref. 6). Thus, it allows in principle very detailed studies of solar radiation reflected from various surfaces even very close to the limb of the earth. Observations of the illuminated part of the disc of the earth are possible every 25 minutes. Therefore, statistical studies are possible for a very great variety of zenith angles of the sun and of combinations of the zenith and azimuthal angles of measurement.

In the preliminary investigations reported here, the reflection characteristics of the earth-atmosphere system are studied with digitized records of nine photographs which were obtained at about 1.5-hour intervals on 21 and 22 April 1967. They cover nearly a full period between sunrise and sunset over the earth's disc.

Further studies with data of other photographs are underway to extend these preliminary results.

ANALYSIS OF DATA

A radiometer or a camera aboard a satellite, having a narrow field of view and observing an illuminated area on the earth's surface, measures only the radiance N_f of solar radiation reflected in its direction. The bidirectional reflectance ρ'_f of this area may be obtained from N_f by

$$\rho'_f(\theta, \psi, \zeta; \mathrm{sfc}) = \frac{N_f(\theta, \psi, \zeta; \mathrm{sfc})}{\cos\zeta \cdot S_f} \left[\mathrm{sr}^{-1}\right] \tag{1}$$

where S_f is the incident solar irradiance in the filter range f of the ATS-1 camera system which is located between 0.46 and 0.65 microns. The angles θ and ψ designate the zenith angle and the azimuthal angle (relative to the sun's ray) of measurement on the observed surface, while ζ is the sun's zenith angle as seen from the observed area. All observed areas were assumed to be located on the earth's surface. The abbreviation "sfc" characterizes the type of the surface.

At the time of our analysis, a conversion of the ATS-1 signals from digital numbers D, which are available on tape, to values of the outgoing radiance was not possible due to the lack of a reliable calibration in radiometric units. Prelaunch laboratory calibrations (Ref. 6), however, showed a nearly linear relationship between the luminance of a quartz iodide light source (in foot-lamberts) and the camera output (in millivolts). The latter was digitized linearly into 255 intervals. Thus, it was assumed that a linear relationship existed between the radiance viewed by the camera and the corresponding digital value D on the magnetic tape. From Eq. (1), then, ρ'_f is linearily proportional to $D/\cos\zeta$. Therefore, in this study the angular dependence of D' given by

$$D'(\theta, \psi, \zeta; \mathrm{sfc}) = \frac{D(\theta, \psi, \zeta; \mathrm{sfc})}{\cos\zeta} \tag{2}$$

is investigated instead of ρ'_f.

The ATS-1 satellite is positioned over the Equatorial Pacific. The mean geographic coordinates of its subpoint on 21 and 22 April 1967 were 150.5°W longitude and 0.05°N latitude. Slight changes in these coordinates of about $\pm$ 0.3 degrees during this period were not taken into account. From a position 35,787 km above this point, that portion of the earth can be observed which is bounded by about 70°W and 230°W and about 70°N and 70°S. This area consists almost entirely of the Pacific Ocean. Only a few small fractions of the observable disc show the land surfaces of North and Central America and, at very large zenith angles θ , New Zealand and parts of Australia. Therefore, the results of these investigations apply only to an ocean-atmosphere system.

The investigation of the dependence of D′ on the angles θ , ψ and ζ requires an accurate determination of the geographic coordinates of the area from which each signal was obtained. In determining these positions, it was assumed that each area was located on the surface of a spherical earth having a radius of 6371 km.

The only known coordinates of the original ATS-1 camera signals in a coordinate system with respect to the spin axis of ATS-1 are the increments of the camera step angle $\Delta \nu$ = 27.06'' arc (Ref. 6) and of the angular distance between two digital values on a scan line $\Delta \mu$ = 8.7891'' arc. The latter is obtained from digitizing the analog signals of a 20-degree scan into 2^{13} = 8192 equidistant digital steps. From facsimile prints* of the digital data D, the number of the scan line which coincides with the earth's equator was determined, assuming that the satellite spin axis is parallel to the earth's rotation axis. This particular scan line was used as the initial value for locating all other scan lines of a given photograph.

These calculations could be performed very easily if the attitude of the satellite were known very accurately. But slight oscillations and motions of the spin axis of ATS-1, which are not recorded on the ground, as well as errors of synchronization of all recording equipment cause perturbations in the pictures. On the original photographs some of them can be observed as irregularities in the shape of the illuminated limb of the earth. Thus, many empirical adjustments were necessary, such as the defining of an "effective" step angle and the shifting of scan lines in order to effect a geographic registration using available landmarks or cloud features whose positions were known. In this regard, a valuable source of information were photographs of the ESSA 3-satellite from

*These facsimile prints were obtained through the courtesy of Mr. C. L. Bristor, Chief of the Data Processing and Analysis Division of the National Environmental Satellite Center, ESSA, Suitland, Md.

which approximate positions of typical cloud features were taken. The only clear observable landmarks were the western coastlines of the United States and Mexico.

The above-mentioned errors in the satellite attitude do not allow an absolute location of the data by an operational computer procedure of better than 1 - 2 degrees of longitude and latitude, even over areas close to the subsatellite point. But an even higher spatial resolution of 0.5 degrees of longitude and latitude was chosen for an analysis grid, expecting that later geostationary satellites would allow this accuracy. Mean values D'' were computed for each grid element from all individual values D' falling within that element. The angular dependence of these averages D'', then, was the subject of these investigations.

The increments of the angles θ, ψ and ζ were chosen to be: $\Delta \psi = 5$ degrees, $\Delta \sin \theta = 0.1$, and $\Delta \cos \zeta = 0.1$.

In addition four types of atmospheric states were categorized assuming, generally, that each increase of the cloudiness of the atmosphere results in an increase of the brightness of a viewed area. Evidence for this assumption is shown in theoretical investigations of the field of solar radiation reflected to space from different atmospheric models (see e.g. KORB, et. al., 1957). In fact, areas of clear atmosphere over ocean surfaces, except when viewing near the specular point of the sun, are the darkest areas in all photographs. Increments of D'' were chosen by experience to categorize the following conditions of atmospheric state:

complete overcast	:	$171 \leq D''$
cloudy - overcast	:	$41 \leq D'' \leq 170$
cloudless	:	$8 \leq D'' \leq 40$

Additionally the smallest values of D'' falling within each combination of the increments of all three angles of measurement were sought. These lowest values of D'', designated herein "minimal reflection", were assumed to represent all cases of a least turbid atmosphere over the ocean surface.

Values of $D'' \leq 8$ were not found over all parts of the illuminated disc of the earth except over areas where the sun's zenith angle was larger than 88.85° ($\cos \zeta < 0.02$). These areas were excluded from our investigations.

Uncertainties in the A/D converter caused considerable additional noise in the data, usually in the form of single noise peaks. A simple "data filter" was designed to reject these noise peaks and to replace them by the arithmetic averages of the adjacent data points. This filter was invoked when increments of the digital value D between two adjacent digital numbers exceeded $\Delta D = 10$ for $D \leq 100$ and $\Delta D = 20$ for $D > 100$. It also checked the "trend" of the data along a scan line, in order to retain such large changes, if they persisted for more than one sample indicating that they were really caused by sharp cloud boundaries rather than by noise. These increments ΔD were chosen by experience.

Fig. 1 shows two parts of a scan line. Symbols + designate unfiltered data, while the data points * are considered to be noise. The filter replaced them by the new data ⊕. This example, shown in Fig. 1, demonstrates one of the worst cases observed so far.

This simple operationally used filter, indeed, might "smooth out" very small, but very bright single clouds over the dark ocean surface. But there was no other possibility to omit the noise from the useful data records.

The response of the camera system and the amplification of all systems involved in producing the digital numbers were assumed to be constant during the entire period of 17 hours spanned by the nine pictures included in this analysis.

PRELIMINARY RESULTS:

The limited number of data obtained so far from only nine photographs did not produce statistically representative averages of D'' for each increment of all three angles θ, ψ and ζ. Especially at larger solar zenith angles ($\cos\zeta \leq 0.8$) there were wide gaps in the fields of D'' (θ, ψ, ζ; sfc). Therefore, in this report only results which were obtained for very small solar zenith angles ($0.9 \leq \cos\zeta \leq 1.0$) are shown.

Figs. 2 and 3 show in polar coordinates the results for the conditions "complete overcast" and "cloudy-overcast". In both distributions a marked increase in the brightness of the earth-atmosphere system occurs within a small range of angles close to the specular point of the sun ($\psi = 0°$; $0° \leq \theta \leq 25.8°$). This might be caused either by specular reflection from the ocean surface in gaps between the clouds and/or possibly from the clouds themselves.

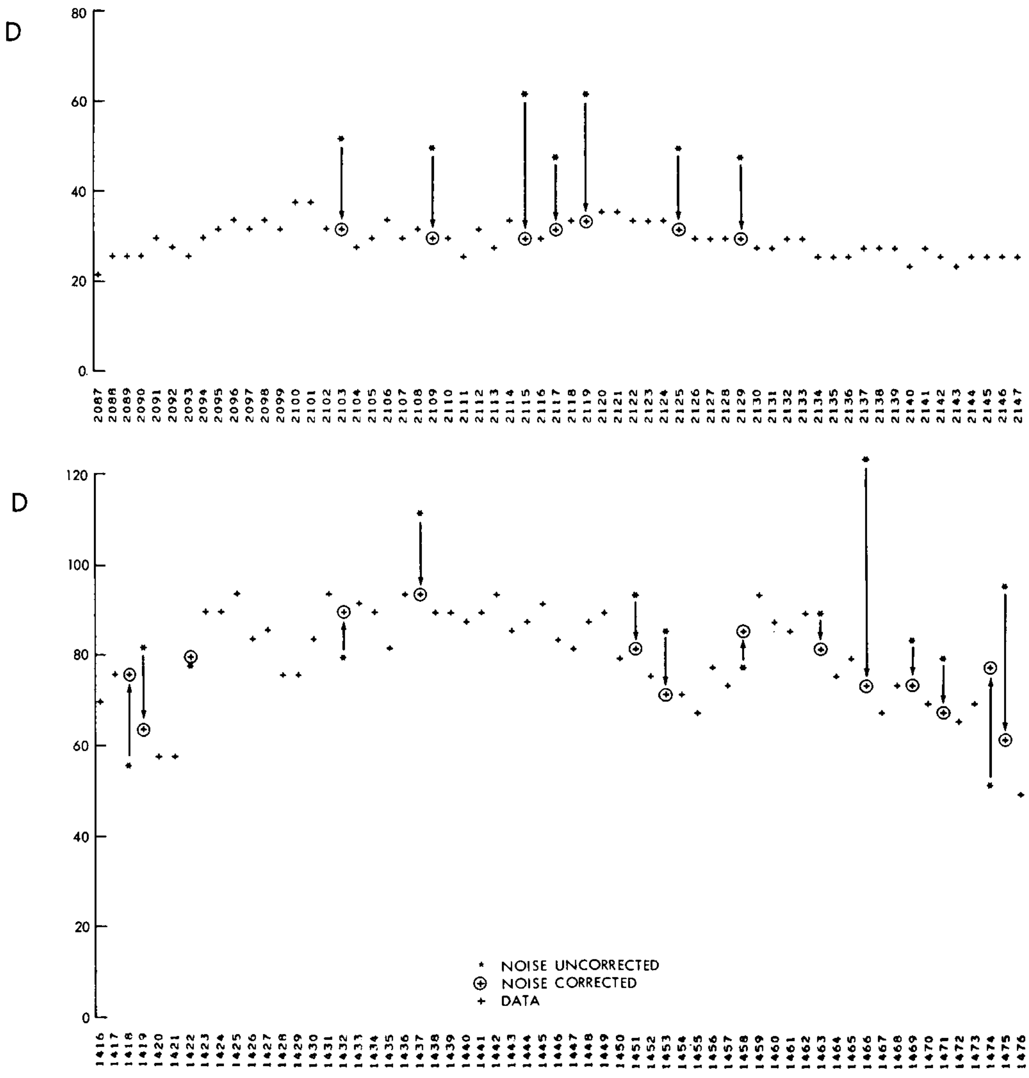

Figure 1. Digital Values D vs. Arbitrarily-numbered Increments of Scan Angle ($\Delta\mu$= 8.7891" Arc), Showing Two Particularly Noisy Sections of One Scan Line. The Results of Applying the "Data Filter" are Illustrated.

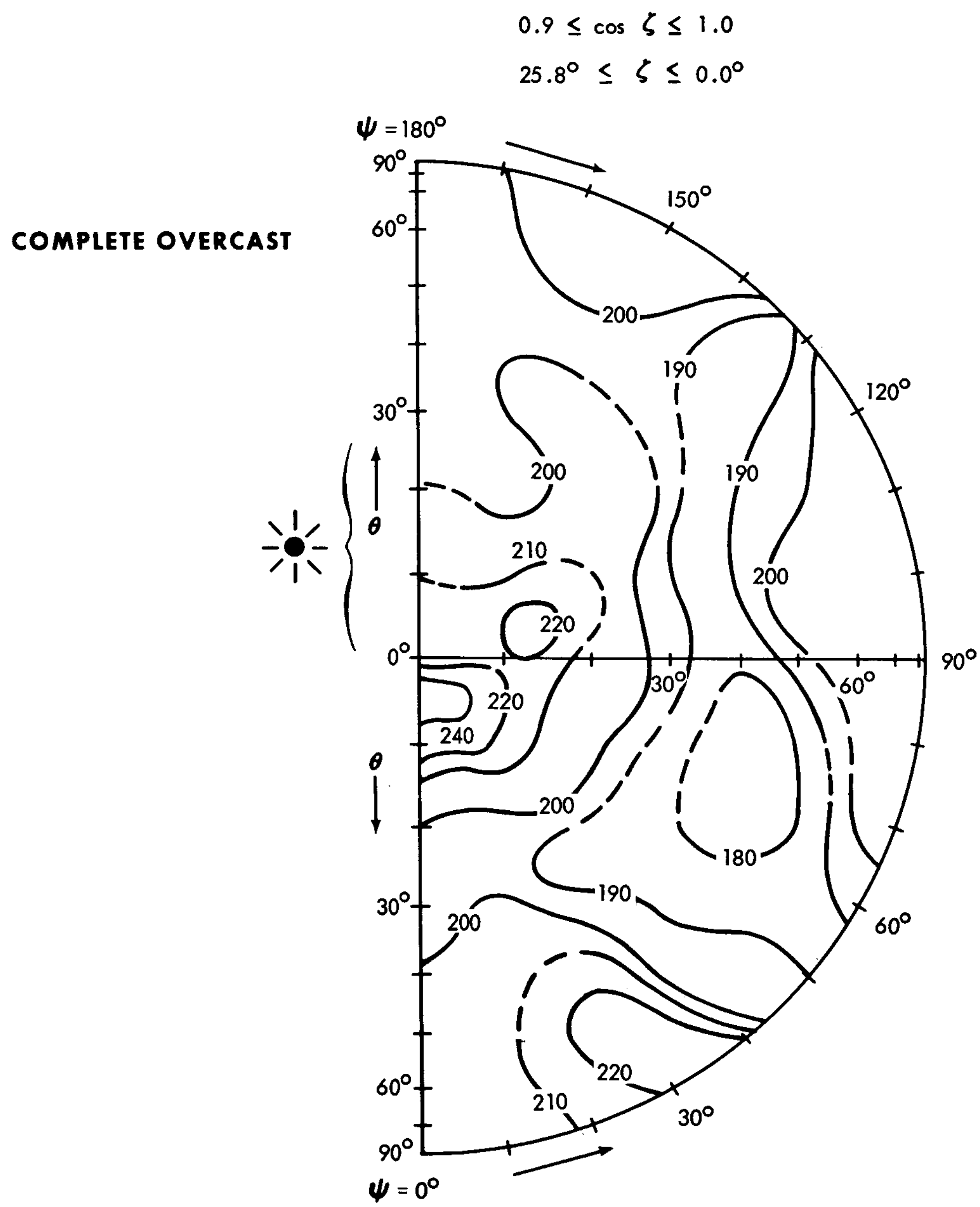

Figure 2. Angular Distribution of the Digital Values D'' (= D/cos ζ) for "Complete Overcast" Conditions

$0.9 \leq \cos \zeta \leq 1.0$

$25.8^\circ \leq \zeta \leq 0.0^\circ$

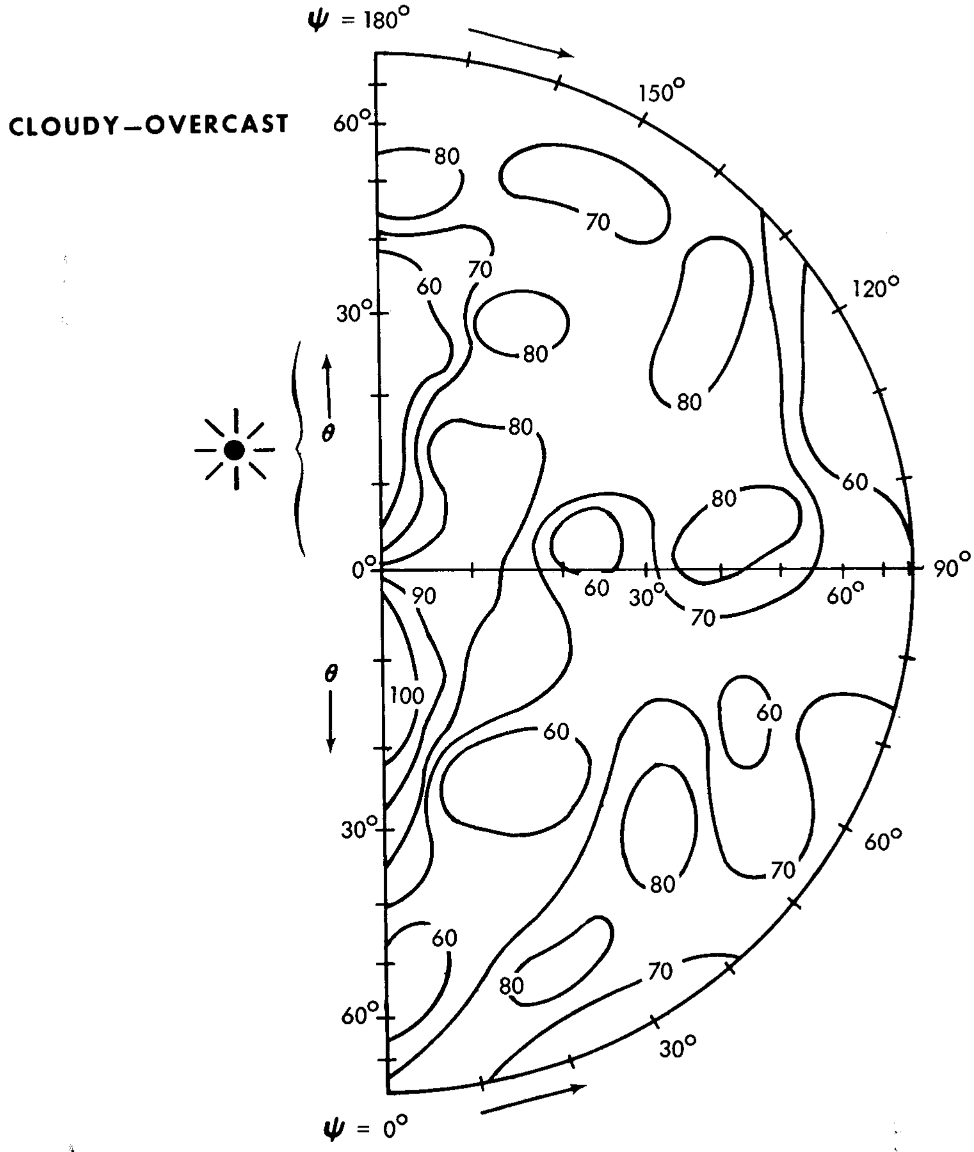

Figure 3. Angular Distribution of the Digital Values D'' (= D/cos ζ) for the Conditions "Cloudy-Overcast"

In Fig. 2 the brightness seems to increase slightly toward the horizon. In both figures there is no definite indication of a maximum caused by direct backscattering, which was found by SALOMONSON (1966) over a strato-cumulus cloud layer.

Evidence of specular reflection and of an increase in brightness toward the horizon is more pronounced in Figs. 4 and 5 which show the angular distribution of D'' for "cloudless atmosphere" and "minimal reflection" conditions. But, here as in Figs. 2 and 3 the bright area around the specular point of the sun extends over a small angular range only. Thus the specular contribution to the directional reflectance (i.e., the total reflectance from a surface into the upward hemisphere for a given value of ζ) is comparatively small.

No special attention is given in this report to the occurrence of other minima and maxima of D'' in Figs. 2 through 5. They might be caused by an accidental arrangement of bright and dark areas in the photographs analyzed so far.

Table 1 lists the total averages of D'', which were obtained by integration of D'' over the two angles of observation, expressed by

$$\bar{D}''(\zeta = \text{const; sfc}) = \frac{2}{\pi}\int_0^{\pi}\int_0^{\frac{\pi}{2}} D''(\theta, \psi, \zeta = \text{const; sfc}) \sin\theta \cos\theta \, d\theta \, d\psi \qquad (3)$$

The total averages $\bar{D}''$ in Table 1 correspond to $(1/\pi) \times$ the directional reflectances of surfaces having the characteristics shown in Figs. 2 through 5. Therefore, one should expect to obtain at least relative information about the directional reflectance (BARTMAN, 1967) of the earth-atmosphere system from these values. If it is assumed that the directional reflectance over very thick clouds (as assumed under "complete overcast" conditions) is about 75%, then the directional reflectance over an extremely clear ocean surface would be only about 8% (Table 1). The slightly higher value of 11% obtained for "cloudless atmosphere" conditions might be due to some cloudiness included in this statistical analysis.

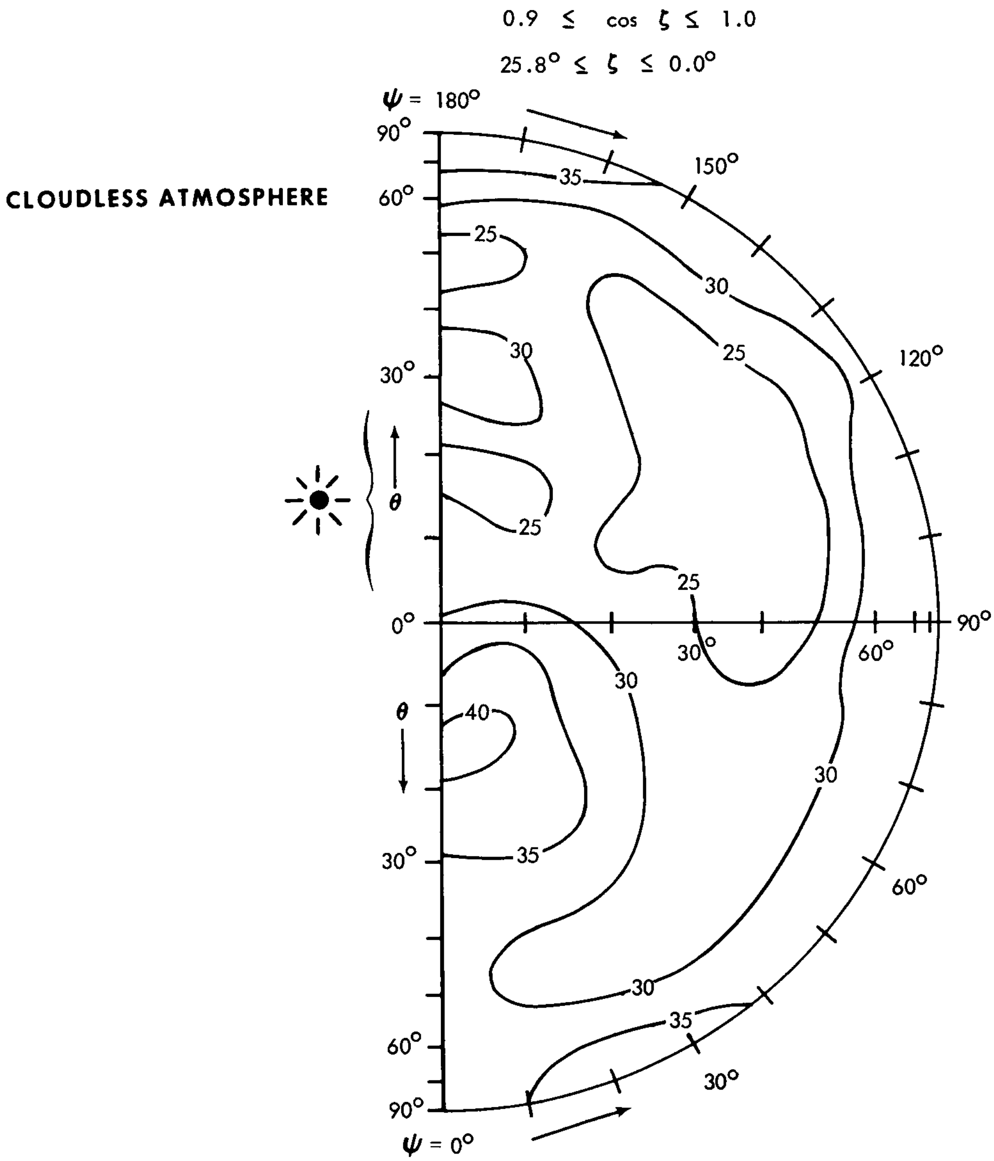

Figure 4. Angular Distribution of the Digital Values D'' (= D/cos ζ) for the Conditions "Cloudless Atmosphere"

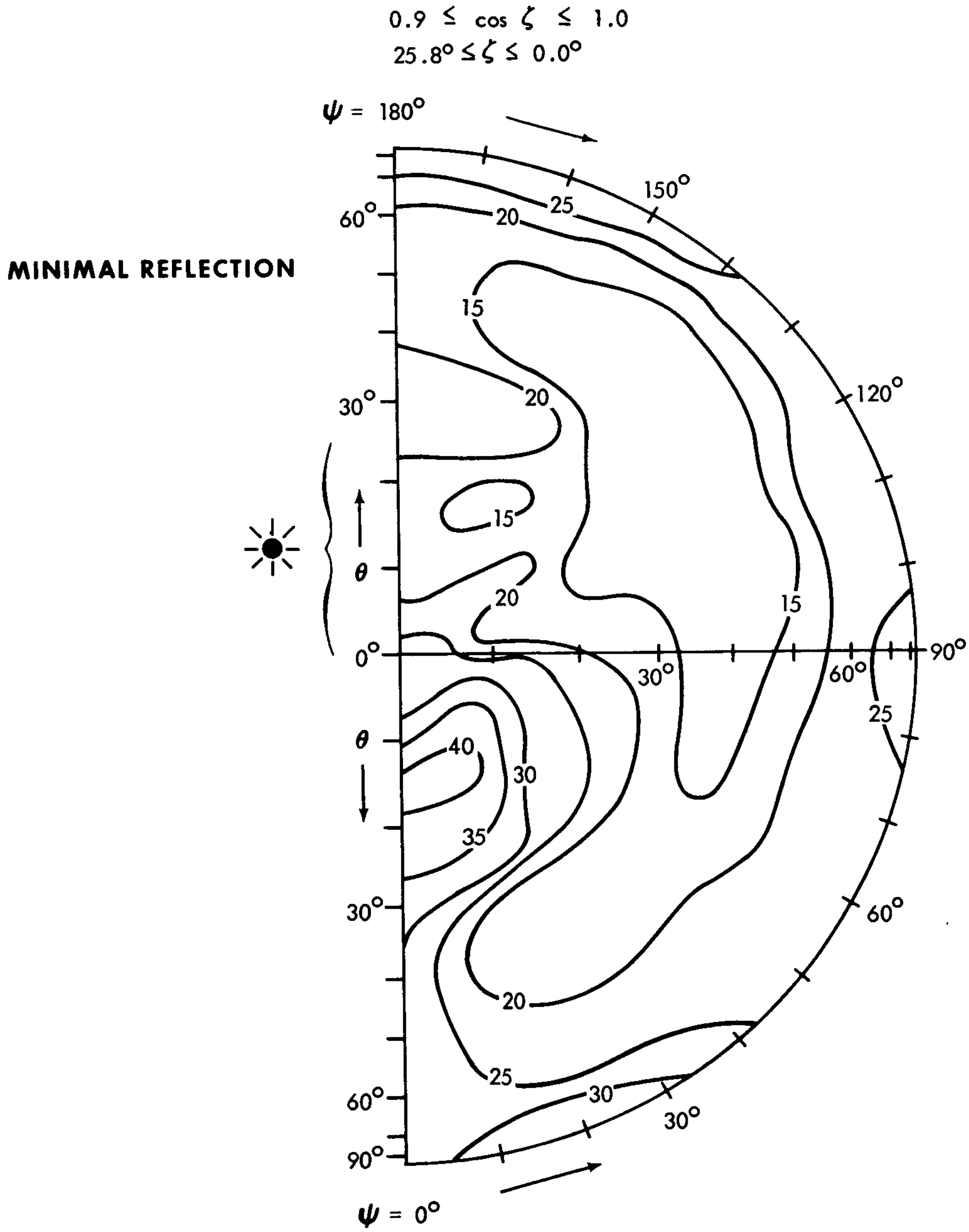

Figure 5. Angular Distribution of the Smallest Values of D″ (=D/cos ζ) Which Are Assumed to Represent Conditions of a Least Turbid Atmosphere Over the Ocean Surface

Table 1

Total Averages $\overline{D}''$, Obtained by Integration of the Angluar Distributions of D'', Shown in Figs. 2 Through 5, Over the Upward Hemisphere

Condition	$\overline{D}''$	Directional Reflectance
complete overcast	197	75% (assumed)
cloudy - overcast	71	27%
cloudless	29	11%
minimal reflection	21	8%

CONCLUSIONS

The preliminary results presented here of the angular dependence of reflected solar radiation in the spectral range 0.46-0.65 microns, obtained from nine photographs of the ATS-1 spin scan camera, indicate that a specular component exists but that it is of little importance to the total directional reflectance for small solar zenith angles. Unfortunately the quantity of data was not statistically representative for all angular increments and, hence, no general conclusions can be drawn. However, the results are encouraging and illustrate the potential of more comprehensive studies of this type, using a more representative sample of data having improved signal-to-noise characteristics.

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